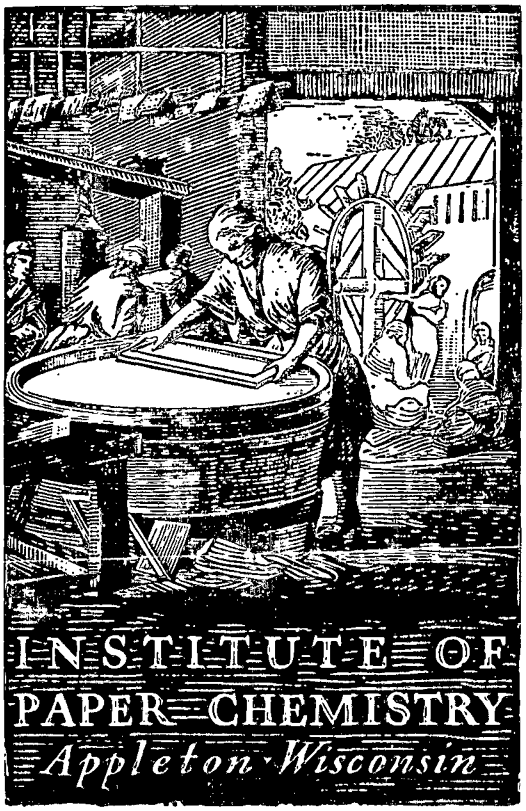

A CRITICAL REVIEW OF CURRENT THEORIES FOR THE REFINING OF CHEMICAL PULPS

Project 3384

Report Three
A Progress Report
to
MEMBERS OF THE INSTITUTE OF PAPER CHEMISTRY

January 9, 1981

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Appleton, Wisconsin

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ABSTRACT

The literature dealing with effects of refining on the structure of individual cellulose fibers is reviewed with an emphasis on creating a universal list of primary effects of beating. The various theories and hypotheses put forward to explain the mechanics of refining are critically reviewed. Less relevant material of this latter subject seems to be avilable, and much of the fundamental and still valid research work in the area is quite old. New experimental evidence is presented in support of a hypothesis that initial stages of refining consist of treatment of flocs instead of individual pulp fibers. The significance of this postulate to refining research is discussed.

The review is partially based on the literature study done by the author during the summer of 1979, when he was a visiting scientist at The Institute of Paper Chemistry. It was first presented at the International Symposium on the Fundamentals of Refining, held at IPC September 16-18, 1980.

ACKNOWLEDGMENT

The author is indebted to The Institute of Paper Chemistry for arranging the visit. The help of the IPC staff working on the refiner research project is also gratefully acknowledged.

INTRODUCTION

The term "Refining of chemical pulp," in connection with papermaking, means mechanical treatment of the chemical pulp fibers in order to render them more suitable for the papermaking. During this review the terms refining and beating are used synonymously. This review is restricted to low consistency mechanical treatment of low and medium yield chemical pulps.

Due to the very high amount of technical literature dealing with various aspects of refining[1], it has been impossible to review all the "current" refining literature. Instead, a method of selective emphasis has been used.

Based on the present information concerning the structure of paper, it is possible to define refining as the process of creating desirable structural changes in the cell wall of the pulp fibers at the expenditure of mechanical energy (Fig. 1) (1). The nature and extent of the desirable structural changes depends very much on the end use properties of the paper grade in question and on the papermaking quality of the unrefined pulp fibers. Unfortunately, the present refining or beating processes also create simultaneously unwanted structural changes, i.e., damage in the pulp fibers. Thus, in the refining process a compromise has to be made between the wanted and the attainable effects of refining on the pulp fibers and on the sheet characteristics. As can be seen from Fig. 1, the papermaker has a large number of processing variables available to affect the result of the refining process. Unfortunately there seems to be no generally accepted theory of refining that would tell the papermaker what is the exact effect of the various controlling variables (shown in Fig. 1) on the structural changes obtained, i.e., on the output of the refining process. Besides, in typical industrial refining, for instance in

[1] About 30-50 major references per year are listed in the annual index of ABIPC.

integrated papermaking, the only active controlling variable of the refining process is the load adjustment.

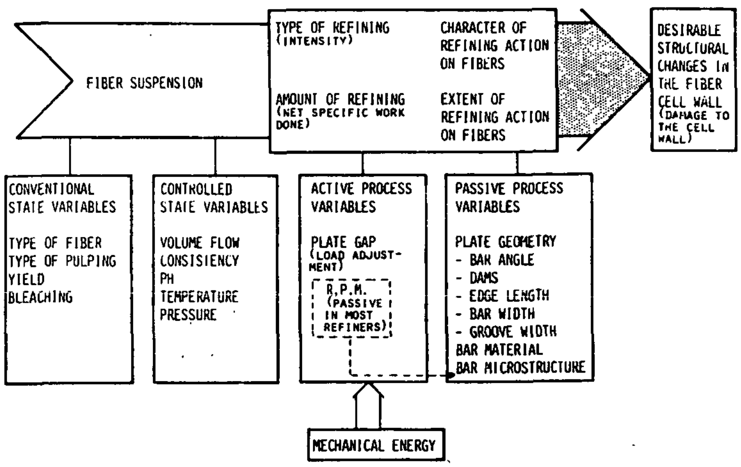


Figure 1. Qualitative Model of Refining Process

The lack of a generally accepted theory of refining may partially be due to the lack of suitable measurement techniques to characterize the structural changes in the papermaking fibers due to refining (2). However, the major reason seems to be the practical need for a shortcut in the chain of reasoning of how to control the quality of the paper through refining (Fig. 2).

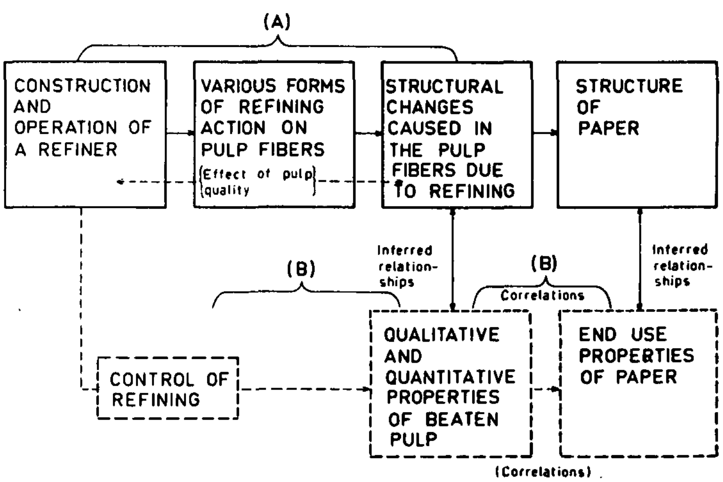


Figure 2. Schematic Representation of the Scope of Theory of Refining (A) and the Area of Common Refining Research (B)

Another reason for the lack of an acceptable theory of refining is probably the fact that since paper is a composite structure, all the structural needs dictated by the end use properties of the paper cannot usually be satisfied through refining of the fibers. Instead a compromise often has to be made between the various structural changes of the fibrous cell wall that are caused by refining. The requirement for an efficient use of mechanical energy in refining also affects the compromise to be selected.

As can be seen from Fig. 2, much of the refining research in the past has been along the lines of pulp evaluation, although in recent years a considerable amount of research has also been directed towards characterizing the refining process. As a result of such characterizing research, technical possibilities to control the refining process have been somewhat advanced.

The increased knowledge concerning the structure of paper[1] and how that is affected by the structure and chemical composition of the component fibers has made it possible to deduce - at least to a certain extent - what the desirable structural changes in the cell wall of the component fibers are in refining. In addition, there also is information about how the unwanted structural changes, i.e., damage to the cell wall, affects the structural behavior of paper in the various end use applications. There seems to be a general agreement of what are the primary structural changes caused by beating or refining (10-15), although the emphasis on what are the important refining actions on fibers seems to generate disagreement between the representatives of the various schools of thoughts (16).

In comparison to the cited advancement of information concerning (a) the structure of paper and how that is affected by the structure of the component

[1] Summed up for instance in the Proceedings of the Fundamental Research Symposiums organized by RPBMA (nowadays BPBIF) (6-9).

fibers, and (b) the primary changes in the cell wall structure caused by refining, very little relevant information has been published over the years about the mechanism (action) that causes the various primary effects of refining in the pulp fibers[1]. In other words, it is not known how the mechanical energy of refining is transferred to the fibers, i.e., what is the behavior of the stock in the refining zone and what is the path of fibers through the refiner. It is believed that as long as this piece of information is lacking, there will be no grounds for the establishment of a "good" theory of refining.

If such a theory were available, it could be used, for instance, in the following cases:

1. Design and selection of the best possible operating conditions for a new refiner that would (see Fig. 2)
   - have a higher energy efficiency than the present refiners
   - be applicable to refining of new types of pulp fibers
   - generate new combinations of papermaking properties into refined pulp fiber, i.e., combinations that are unattainable with present refiners.
2. Choice of the optimal process conditions for an existing refiner taking into account the process modifications that are easily carried out in the process of refining (Fig. 1).

The expenditure of electrical energy in refining of chemical pulp fibers is around 720-1800 MJ/t. pulp (200-500 kWh/t.). For a papermill producing about 100,000 t./a, the direct energy cost of refining will easily mount to about 0.3-0.6 million U.S. dollars annually. Although this sum is not a very large manufacturing cost on a relative basis, it represents a considerable potential for energy saving and for

[1]This same fact was emphasized also by Atack in his 1977 review of beating (15).

profit making. This is so because out of the total cost of refining, including capital cost and replacement cost of the worn-out tackle or plates, the role of direct energy consumption is dominant, i.e., about 80% (17,18).

Thus the savings obtained can easily pay back an investment for a new set of refining tackle or for a change in the rotational direction of the rotor.

PRIMARY EFFECTS OF REFINING ON FIBERS

For a thorough analysis of this subject matter one is referred to the book by Emerton (11) and to the reviews by Higgins and Yong (12), Fahey (14), Atack (15), and Clark (16). Only a concise representation of the effects of refining on the structure of the fibers is given here based on an earlier review of the matter (13) and supplemented with selective references to later publications.

It is somewhat difficult to define the primary beating effects on the structure of the fibers since fibers themselves form a very heterogeneous source of material. One needs only to point out that fibers in a given pulp have a large distribution of sizes (length, diameter, thickness of the cell wall, fibrillar angle) and that the chemical composition of the cell wall and distribution of the main chemical constituents through the cell wall vary considerably. Besides, the unrefined fibers already have some structural damage in their cell walls (92).

We can define the primary effects of refining as such changes in the structure of the fiber; with these effects it is - at least in theory - possible to differentiate between a refined fiber and an unrefined one. A further requirement for the primary effect of refining is that it cannot be divided into components. However, there is no need to restrict the appearance of the primary beating effects on the fibers to only one type of an effect per a particular fiber. On the contrary, due to the fact that refining is carried out in water, and due to the mode of transferring mechanical energy into the fibers during refining, it is easy to visualize that many of the primary beating effects do in fact occur simultaneously in a given fiber.

Besides being of fundamental nature and of simultaneous occurrence, the primary beating effects have to be defined also as irreversible structural changes (19). Because the refining process, i.e., the mechanism of transferring mechanical energy into fibers and creating primary beating effects in the fiber, is controlled by some type of probability function (4) and because of the heterogeneous flow pattern through the refiner (20), the distribution and extent of the primary beating effects among the refined fibers is very heterogeneous. In other words, it is possible to find fibers that have received practically no refining treatment and fibers that have received refining action well over the average amount (21-23). Besides, the type and extent of refining treatment within the fiber is localized (92). One may also reach conclusions regarding the heterogeneous nature of the refining process (24) based on the change of the fiber length distribution curve during refining, i.e., that after considerable refining and cutting of fibers, it is still in many cases possible to find "uncut" original fibers in the stock.

ROLE OF WATER IN REFINING

Refining of chemical pulp fibers differs from crushing ore in two respects: (1) the purpose of refining is not solely reduction of size and (2) refining is carried out under the plasticizing action of water (25). Since the pioneering study by Kress and Bialkowski (26), there have been other studies made in order to find out the mechanism of water in refining (27-29). It has been shown that dry grinding easily generates free radicals in the various chemical constituents of the cell wall

(30). Thus it is clearly established that water acts as a plasticizer and protective medium in the refining process.

Because of the presence of water in refining and because of the structural features of the cell wall, one could very well state that the main effect of refining is an opening up of the fiber structure. That is not the case if the refining is done in air with a conventional low consistency refiner equipped with a knife tackle (31). Using normal bar clearance in such a refiner, the chemical pulp fibers are quickly physically and chemically decomposed without any development of internal or external fibrillation.

CLASSIFICATION OF THE PRIMARY BEATING EFFECTS

The old refining literature usually listed three primary beating effects, i.e., structural changes in the fibers due to refining. These are: (1) cutting and/or splitting of the fibers, (2) external fibrillation of the fiber surface and (3) hydration of the cell wall material. A recent review of the mechanical treatment of chemical pulps (14) speaks about only two refining actions: (a) breakage of intrafiber hydrogen bonds and replacing of them with fiber-water hydrogen bonds, and (b) breakage of covalent bonds.

Table I summarizes the primary effects listed by various authors (12-14, 16,32). As can be seen, disagreement between the depicted lists is small. It is a matter of taste if the production of fines needs to be listed as a separate primary beating effect[1]. Due to the heterogeneity of the chemical pulp and because of the basic structure of the cell wall, it is to be expected that all the listed effects occur simultaneously, but the extent of their occurrence can vary considerably. It is, however, difficult to decide which of the listed primary beating effects is

[1]The order of presentation of the effects by no means implies any preferable order of significance or order of probability of occurrence.

TABLE I. PRIMARY BEATING EFFECTS (STRUCTURAL CONSIDERATIONS)

HISTORICAL	FAHEY (14)	HIGGINS AND YOUNG (12)	GIERTZ (32)	CLARK (16)	EBELING (13)
CUTTING/ SPLITTING	BREAKING OF COVALENT BONDS	FIBER SHORTENING	CUTTING AND CRUSHING	SHORTENING	FIBER SHORTENING
EXTERNAL FIBRILLATION		EXTERNAL FIBRILLATION	SUCCESSIVE CLEAVAGE OF EXTERNAL LAYERS OF THE CELL WALL AND SUBSEQUENT BREAKING AWAY OF THESE LAYERS	EXTERNAL SPLITTING	SUCCESSIVE CLEAVAGE OF EXTERNAL LAYERS OF THE CELL WALL AND THEIR SUBSEQUENT BREAKING AWAY *
HYDRATION	INTRAFIBER H-BOND BREAKING	INTRAFIBER H-BOND BREAKING	INTRAFIBER H-BOND BREAKING	INTERNAL SPLITTING	DELAMINATION OF INTERNAL CELL WALL LAYERS *
		PRODUCTION OF FINES		(PRODUCTION OF DEBRIS) *	(* = SEE ABOVE)
			CREATION OF DISLOCATIONS	(LONGITUDINAL COMPRESSION) *	LOCAL DISLOCATIONS OF THE CELL WALL STRUCTURE
				* SECONDARY EFFECTS	DISSOLUTION OF THE CHEMICAL COMPONENTS OF THE CELL WALL AND SIMULTANEOUS FORMATION OF COLLOIDAL CARBOHYDRATE SOLUTION ON THE SURFACES AFFECTED

few results which show that part of the cell wall material gets dissolved during refining (26,38,49-53). This may be taken as indirect evidence for the appearance of molecular fibrillation, since molecular fibrillation is a prerequisite for the complete dissolution of the polymeric components of the cell wall. The importance of various cations on the pulp and paper properties (54) may also be taken as an indication of the presence of molecular fibrillation. Similarly, the increased beating response of high yield pulps and of recycled old corrugated containers (55,56) due to ozone treatment would seem to indicate the presence of molecular fibrillation at least on the external fiber surfaces. Besides, many researchers, in the area of refining, have emphasized "molecular fibrillation" as one of the most important refining results (11,26,32,38,40,60-63). When speaking about molecular fibrillation and its role in refining and papermaking, one should also keep in mind that it is very difficult if not impossible to beat a high alpha-cellulose pulp.

Creation of New Particles

This class of primary beating effects can also be divided into three subclasses based on the size of structural units involved: (a) cutting[1] of fibers, (b) cutting and/or splitting loose of cell wall lamellae and macrofibrils, and (c) dissolution or cutting away of the polymeric molecules of the cell wall. The cutting of fibers and detachment of large parts of lamellae is called "generation of fines" and there is plenty of experimental evidence about this primary effect of beating. The detachment of lamellar and macrofibrillar matter from the cell wall is often called "generation of crill," and there is also plenty of experimental evidence about it since the introduction of the term by Steenberg, Sandgren and Wahren (64,65). However, there seems to be a considerable disagreement about the significance of fines and crill to the structure and properties of the paper made from

[1]Splitting has been omitted since, due to the considerable helical winding of microfibrils in the S_2 - layer of wood pulp fibers, complete splitting of such fibers is highly important.

refined fibers containing fines and crill. A cursory review of the literature indicates that those in favor for a significant role of fines in the structure of paper (66-72) slightly outnumber those of the opposite opinion (15,16,33,65,73,74).

There exists also plenty of experimental evidence for the dissolution of the cell wall material due to refining (26,49-52). The reported amounts of material dissolved in medium to long refining vary from 0.5-4.0% for softwood pulps. More material is generally dissolved from high yield pulps.

Generation of Structural Damage and Modification

This class of refining action is not as clearly defined as the two previous classes. The following subclasses can be separated: (a) cutting of fibers or lamellae[1], (b) generation of axially compressed zones[2] (misalignment zones, dislocations, kink bands), (c) partial cleavage of the cell wall, and (d) creation of invisible weak zones which will lower the cell wall rigidity so that it will collapse[3] locally under drying or so that it will break during deformation[4] associated with tensile or tear loading. There is also considerable evidence about large changes in crystallite sizes and microfibrillar orientation during refining. Since similar changes can also be caused by stresses induced by drying, these structural modifications have been left out as primary effects of beating.

[1] Generation of fines may be a desired refining action in many cases although it takes place through structural damage.

[2] Generation of axially compressed zones may be a desired refining action, for instance, in the manufacture of sack paper.

[3] In many cases the collapse of the lumen is a prerequisite for intense bonding between the fibers.

[4] It should be noted that although refining generates all wall "dislocations," the tensile strength of refined fibers does not decrease but increases (81,93). This only shows the importance of stress equalization between the fibrils and the importance of drying conditions for the tensile strength (86,87). Apparently the dislocation zones are capable of healing under suitable drying conditions.

The direct evidence for fines and crill production has already been cited (see Creation of New Particles). There is also direct evidence for the formation of axially compressed zones in refining (36,44,76-85). It is quite obvious that these misalignment zones play a very significant role during the consolidation of the sheet structure. The mechanisms involved are the Page and Tydeman micro-compression effect (86) and the related Jentzen (87) and negative Jentzen effects (88), which lead to a paper structure where there is plenty of opportunity for dissipation of strain energy (89).

There is no direct quantitative evidence for the partial cleavage of the cell wall due to refining, but in many micrographs of the refined fibers one can observe such cleavages (6,11,12,66). The existence of such cleavages can also be inferred from the cutting of fibers in refining, because it is very probable that not all of the refining action tending to cut the fiber will actually do so.

The collapse of the cell wall lumen due to refining is well accepted (48,90). Many papermakers even believe that collapse of the lumen is a structural prerequisite for strong fiber-to-fiber bonding. However, in the case of certain printing paper grades, the collapsing tendency may be viewed as a structural weakness, because it will cause a drop in the light scattering power of the sheet. Similarly, in the case of linerboard, the collapse of lumen with the simultaneous increased fiber-to-fiber bonding may cause a decrease in the buckling resistance of the linerboard. It has been reported (91) that ultrasonic refining does not weaken the cell wall to the same extent as mechanical refining does, and thus there is less fiber collapse during drying. This can be an advantage in obtaining sheets with higher bulk and tearing strength at a medium level of tensile strength.

One can consider that cutting and partial cleavage form one end of a "damage distribution" curve caused by a certain type of refining action on the fibers. Besides these two visible damages, there will also be some "invisible" weakening of the cell wall that could initiate a final rupture of the sheet in tensile or tear deformation. It is generally agreed that the points of localized damage to the cell wall will show as points of ballooning of the fibers when placed in strong swelling agents (92).

Thus, the last class of primary beating effects "Structural damage" is a heterogeneous class of effects of various magnitude. In some paper grades the "damaging action" of the refiner may be a very desirable beating effect, in some other grades it is totally undesirable.

Due to the basic structure of the chemical pulp fibers and due to the fact that refining is carried out in water, it is impossible to control the refining so that one obtains specifically only one of the listed primary beating effects (32). It is also easy to accept the view expressed by Steenberg (4) that it is impossible to characterize the beating result by only one single parameter.

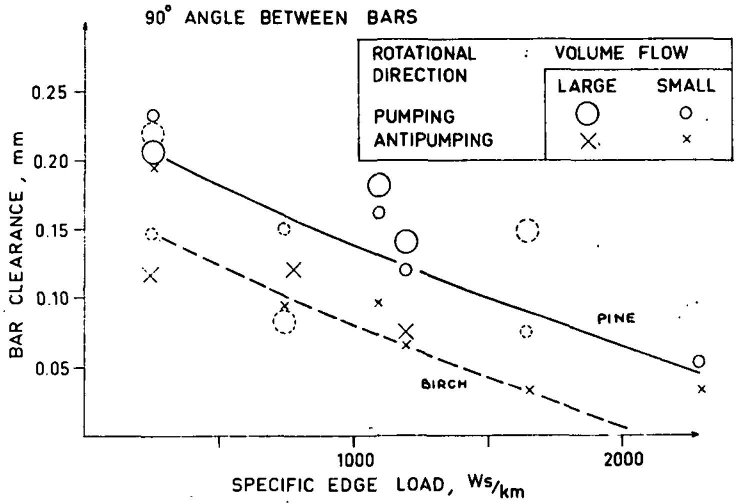
HYPOTHESES FOR MECHANICS OF REFINING

As was already stated, we know very little of the actual action inside the refiner and how this refiner action changes with refining conditions, i.e., the exact transfer mechanics of energy into the fibers are still unknown. In the following, a review of the various hypotheses and theories put forward for describing the mechanism by which fibers interact with the refiner is given. Before doing so, a short summing-up of the present facts of refining are presented, as well as a short description of the current knowledge of the refiner as a piece of hydraulic machinery.

CURRENT FACTS ABOUT THE REFINING PROCESS

All the beating machinery since the invention of the hollander 300 years ago are based on treating the fiber between bars having a relative motion and being loaded against each other in the presence of water. It is well established that, at the consistencies used in conventional beating and refining (2-6%), the fibers do not move independently from each other but instead they form networks, which break and reform continuously. In other words, fibers are present as flocs in low consistency refining.

For refining to take place, the gap between the land areas of the bars has to be small enough, i.e., in the order of a few fiber diameters. It is well established that a water film alone will not support the compressive load exerted on the film between the surfaces of the refiner. When fibers are present in the water, the load carrying capacity (=gap) of the stock depends on the type of fiber (94-97), on pulp drying (95), on shaft power (or loading of the refiner)(94,97,98), on rpm, internal flow field, hydraulic pressure, direction of rotation, and consistency (95,97,99,113) and on the amount of refining absorbed by the fibers (94-90,100,101,113)(Fig. 3). In this connection it should be noted that the load carrying capacity of a conical refiner and of a hollander, for instance, is quite enormous during refining. When these machines are loaded with pure water, one usually obtains a certain position at the loading device, where the noise generated by the bars is so high that one concludes "there is a bar-to-bar contact." However, during refining one has to go beyond the previous mark quite a lot before the machine starts to pick up load (102,103). The load carrying capacity of the stock to be refined is so high that it actually deforms the refiner or beater (133).



3. Dependence of Bar Clearance on Operational Conditions in a Conical Refiner in the Beginning of Refining (750 rpm)

Although the stock has a load carrying capacity, the land areas in industrial refiners often contact each other in a random manner[1]. This contact will deform the bars; the extent of deformation being dependent on the metallurgical properties of the bars (hardness) and load on the bars (cold hardening). A hypothesis has been proposed, that the wear of refiner plates, which is 40-50 times faster with pure water in between the plates than with 1% stock, is due to abrasion proceeding through minute fissures and impact loadings of these (104). A figure of 20 mg/kWh was given as a specific rate of wear of disc refiner plates.

[1]The contact seems to be more pronounced in the areas where the relative land area in the direction of flow changes suddenly or where there are dams in the grooves of the tackle, or where there are large changes in the orientation of the grooves (130).

The refining results seem to be affected to a large extent by the material of the bars and by the extent of wear (rounding or chisel edge formation) of the edges of the bars (5,95,103-108). A hypothesis has been proposed that plastic refiner plates, due to their softness, will provide a more even distribution of refining results on fibers (109). It has been quite common to recommend a specific metal for a specific refining job, and softer metals were recommended for fibrillating type of refining (110). It has also been shown that, as the refining consistency goes over 10%, the effect of bar edge geometry on refining results practically disappears (111). Refining researchers know how critical the condition and method of conditioning of the bars of the Valley-hollander are for the beating result (112).

THE REFINER AS A PIECE OF TURBOMACHINERY

The conventional bar equipped beater or refiner can be considered as a piece of hydraulic machinery. The simplest case is that of a brake (block, conical, disc). The appropriate formulas have been given, for instance, see reference (114). Results obtained with the brake concept show that when the backed-off idling power correction is done, practically all the refining energy appears as heat (97,115-117)[1].

Dalzell (118) described the power requirements of refining to be composed of two terms (a) fluid film power consumption (brake power, P_1) and (b) pumping and circulation power (idling power, P_2). These two power terms are given in Eq. (1) and (2)

$$P_1 = k_1 \frac{\mu}{\Delta^n} DL \cdot \varepsilon \cdot v_{av}^2$$

[1]Theoretical considerations, based on the heat of wetting of the new surfaces generated, could perhaps lead to a prediction that more heat should be recovered as is directed into the refiner in the form of mechanical work.

$$P_2 = k_2 \, DL \cdot v_{av}^3 \quad (2)$$

where

k_1, k_2, and n are constants

μ = viscosity factor (increases greatly with consistency)

Δ = average gap between land areas of rotor and stator

D = effective diameter

L = effective "bar" length

ε = contact area ratio (of the total available area)

v_{av} = effective peripheral speed

According to the author, the disc refiner can have the narrowest grooves between the bars because it is easier to convey the pulp in this type of refiner due to the high centrifugal effect. Dalzell also indicates that, above an efficient peripheral velocity of 25 m/s, the idling power is doing some useful work on the fibers.

Banks (119) maintains that the total power requirement of a refiner is made of three components: (a) power losses due to the whirling of disc in the stock (generation of turbulence in the backed-off position), (b) power losses due to the pumping effect (in unloaded position), and (c) power absorbed in useful attrition work. He gives the following formulas for these three components of refining:

$$P_1 = k_1 D^5 \omega^3 \quad (3)$$

$$P_2 = k_2 D^2 \omega^2 \quad (4)$$

$$P_3 = k_3 f F_t D \omega \quad (5)$$

where

k_1, k_2, k_3 are constants

D = effective disc diameter

ω = angular velocity

f = effective friction coefficient

F_t = axial thrust of the rotating shaft

Banks also notes that due to the high centrifugal action helping the transport of fibers, disc refiners can have smaller tackle elements than the fillings of a conical refiner or a hollander. Based on experience he also gives the following engineering guide values for the effective peripheral speeds of various types of refining operation:

(a) 20 m/s, when the predominant characteristic is fiber length control

(b) 25 m/s, when one wants to obtain a balance between fibrillation and fiber length control

(c) 30 m/s, when the predominant characteristic is fibrillation

(d) 35 m/s, when good deflaking or defibration characteristics are wanted

For high energy efficiency the lowest possible speed should be selected. Similarly, based on experience, it is stated that the bar widths should be around 3 mm for case (a) and wider, about 5-6 mm, for case (c). The grooves should be sufficiently narrow to provide an efficient refining action but wide enough so that the stock will pass through; a value of 3-5 mm is suggested as a practical value provided the stock is well fibrillated. A groove depth of 6 mm is recommended as a compromise for good throughput and efficient refining action (proximity factor). A minimum consistency of 3% is advocated in order to maintain the fiber film even at high specific loading values.

Herbert and Marsh (120) give in essence a similar breakdown for the total horsepower requirements of the refiner, as did Banks (119). However, the formula for the power requirement for work absorption is different.

$$P_3 = K_d D_i (D_o^2 - D_i^2) \tag{6}$$

where

K_d = disc friction constant, which includes the coefficient of friction between fibers and plate and between fibers themselves as well as the average pressure between the plate "contacting" surfaces

D_i = inner diameter of the disc

D_o = outer diameter of the disc

ω = angular velocity

Based on the formula of Eq. (6), the authors claim that the present disc refiners do not have an optimal ratio D_i/D_o (should be = 0.6) but operate at a too small ratio and thus are less energy effficient. With the proposed improvements, in the ratio D_i/D_o, the authors claim that the energy efficiency of a refiner could be raised from 67% to 72%. The effect of the disc grooves was shown to be a tripling of the hydraulic losses due to turbulence.

Pashinskii (121) has derived a modified Bernoulli-equation for the internal flow phenomena of a refiner. His derivations predict a reverse flow in the stator grooves of the refiner and a mixing flow between the rotor and stator grooves. This phenomenon was actually observed in mill scale refiner trials by Halme and Syrjänen (20,122). Reverse flow has also been reported by Herbert and Marsh (120). Pashinskii suggests that the number of zones, where intermixing of stock between rotor and stator grooves takes place, should be maximized in order to achieve an efficient refining.

Leider and Nissan (117) have considered the power requirement for the actual refining process (total power - idling power) for two hypothetical cases. In the first case it is assumed that the pulp suspension behaves like a solid, i.e., it dissipates energy by disc friction and heats up. In the second case it is assumed that the pulp suspension in between the rotor and stator land areas behaves like a fluid, i.e., it dissipates energy through viscous phenomena in the presence of a shear field.

For the solid continuum case, the net power requirement of refining is related to the operational parameters as follows:

$$P_{net,s} = k_1 \varepsilon^2 \omega f \overline{P}_p (D_o^3 - D_i^3) \tag{7}$$

where

k_1 = constant = $\frac{\pi^2}{6}$

ε = fraction of refining area filled with "lands"

ω = angular velocity

f = effective coefficient of friction for fiber-disc combination

$\overline{P}_p$ = average plate pressure over the involved surfaces

D_o = outer diameter of refining zone

D_i = inner diameter of refining zone

Treating the fiber suspension as a homogenous fluid yields

$$P_{net,f} = k_2 m \varepsilon^2 \omega^{n+1} \frac{1}{(n+1)^n} (D_o^{n+3} - D_i^{n+3}) \tag{8}$$

where

m = viscosity of pulp suspension in the case of laminar flow field, and in the case of a turbulent flow field

= (density)·(Prandl's mixing length)^2

n = 1 for laminar flow field, and

= 2 for turbulent flow field

Δ = gap between the rotor and stator land areas

One can conclude from the previous review that the net refining power requirements are related either to solid friction or to fluid friction between the opposing land areas of the rotor and stator tackle. In the first case the axial thrust appears as the driving force for the energy transfer from the tackles to the medium to be refined and in the latter case the controlling factor is the gap between the tackles. The gap and the axial thrust, however, are not independent, since the gap decreases as the axial thrust to the rotating shaft is increased.

It is most probable that both direct disc friction (metal to fiber and metal to metal) as well as viscous dissipation will absorb the net refining power. This is backed up by the observation that pure water will soon heat up if moderate refining power is used, but at the same time pure water will not support the actual refining power, i.e., the plates will clash (117). But if fibers are present in the fluid, a high refiner load can be applied, indicating a friction phenomenon between the land areas in close contact to each other (see Current Facts about Refining Process, "gap during refining").

Recent studies have shown that the hydraulic pressure pulses inside a refiner are very small. In one case values between 0.003 and 0.01 bar (123) and in the other case values between 0.1 to 0.5 bar (97) were reported. These values seem to be so small that a direct refining effect by such hydraulic pulses is highly improbable. On the other hand, direct visual observations have shown that cavitation quite often occurs close to the trailing edges of the rotor bars (124,125). It has even been claimed that by increasing the occurrence of cavitation, the efficiency and speed of refining can be increased (126). The large scale occurrence of cavitation (125) may well explain the common recommendation of modern refiner equipment manufacturers, i.e., the refiner must be placed so that it operates under considerable hydraulic pressure.

The cited studies, where the refiner has been analyzed as a piece of turbomachinery, seem to indicate that direct bar-to-fiber contact and intense fiber-to-fiber contact are involved in the refining process. These studies, however, leave open what is the exact mode (or modes) of transferring the energy impacts into the cell wall. In other words, they do not clarify the actual mechanics of the refining action, i.e., is it, for instance, mainly through the action of the leading edge of the bars or through a crushing and bruising action between the opposing land areas of the rotor and stator bars. Besides, the turbomachinery studies by no means describe the transport phenomena of fibers to the position of achieving the refining action, since such studies do not tell anything about the path of average fiber through the beating machine and how the operational parameters affect this path.

MECHANISMS FOR ABSORPTION OF REFINING ACTION INTO FIBERS

Many hypotheses have been put forward during the years to account for the various modes of the absorption of refining work by the fibers. The historical presentations of the action of the beater to individual fibers were deduced from the effects produced on individual fibers. Usually only two types of work transfer mechanisms were accounted for: namely (a) cutting of fibers between closing bar edges and (b) brushing, crushing, bruising, and/or rubbing of fibers between the opposing land areas of stator and rotor bars (127,128). A large number of formulae have been developed over the years to characterize the cutting action or the fibrillating action of the beater. These formulae have been summarized by Halme (129). One may conclude the historical phase of refiner action on fibers by the following (127):

1. Using a light concentration of stock in the beater with sharp tackle of hard metal and bringing the roll down hard, one obtains quickly a "free" (fast-draining) stock, where the fibers are chopped and cut up.

2. Conversely, with the same furnish but of a thicker consistency and using a blunt tackle of softer metal, one obtains a "wet" (slow-draining) stock by gradually bringing the roll down to a fairly hard rub over a period of several hours.

The time of refining *per se* was not considered to be a criterion of quality.

The classification of the present theories or hypotheses for the transfer of the refining action into the fibers may be done as shown in Table II. This classification is somewhat arbitrary. Many of the listed hypotheses cover only a small area of the refining mechanics and they should perhaps be listed as opinions instead of hypotheses. Along with the introduction of the various hypotheses, experimental evidence in favor or against the proposed mode of transfer of refining action is reviewed.

Fibrage Theory

Smith proposed in 1922 (131) that a beater bar moving through stock collects a beard or fibrage of fibers on the leading edge as does a bedplate bar

TABLE II. PRESENT HYPOTHESES FOR REFINING MECHANISMS

AUTHOR	CLASSIFICATION: NAME	TYPE
SMITH (1923) GONCHAROV (1971)	FIBRAGE	QUANTITATIVE
RANCE (1951) STEENBERG (1951) GONCHAROV (1971)	LUBRICATING SHEAR	QUALITATIVE
DANFORTH (1962) VAN STIPHOUT (1964)	TYPE AND DEGREE OF TREATMENT	QUANTITATIVE
BRECHT AND COWORKERS (1964) SOVIET SCHOOL OF REFINING RESEARCH	(INTENSITY/EXTENT SPECIFIC EDGE LOAD/ NET ENERGY CONSUMPTION)	SEMIQUANTITATIVE
LEIDER & NISSAN (1977) KLINE (1978)	(NUMBER OF IMPACTS/ NET ENERGY PER IMPACT)	
HALME (1962) PASHINSKII (1964) FOX AND COWORKERS (1978)	TRANSPORT PHENOMENA I (EMPHASIS ON FLOW BEHAVIOR)	QUALITATIVE
KORDA (1959) ARJAS AND COWORKERS (1969) FOX AND COWORKERS (1979)	TRANSPORT PHENOMENA II (EMPHASIS ON RESIDENCE TIME DISTRIBUTION)	QUALITATIVE
STEENBERG I (1963) GIERTZ (1964) CLARK (1977	DESCRIPTIVE CONSIDERATIONS	QUALITATIVE
STEENBERG II (1979)	(OOZING/CONSOLIDATION)	
PAGE AND COWORKERS (1962) BANKS (1967) EBELING (1979)	TREATMENT OF FLOCS	QUALITATIVE

with stock travelling over it. The beating action is assumed to be caused (a) by the moving bars shearing through the fibrage (cutting action) when a pair of bar edges cross over each other, or (b) by the bar and fibers on the bar edge sliding under pressure over the pile of fibers forming the fibrage on the second bar edge (wet beating action)(Fig. 4). Cutting does not even require the bars to come in contact since shearing effect on compressed fibers is thought to be sufficient to give a cutting action.

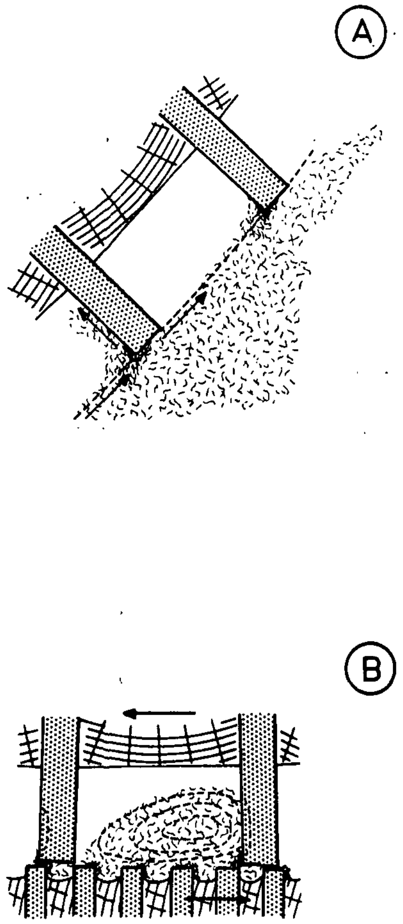


Figure 4. Formation of Fibrages on the Flybars (A) and Bedplate Bars (B) in a Beater (Smith, 1923)

Smith considered the fact that (a) the wear of the front surface of the flybars occurred 2 mm above the leading edges, when beating pigment-containing stock and the fact that (b) when a narrow rod with a square cross section was moved by hand through the stock, the rod collected fibrages and (c) that on an accidental breakdown of a Jordan refiner, fibrage was observed on the rotor bar edges as evidence for his fibrage theory of refining.

Based on the fibrage hypothesis, Smith also derived formulae for the capacity of the beater and for controlling the type of the refining action on fibers. Since the load of the beater roll is supported by the fibrages, i.e., by the flybar edges, Smith introduced the term "actual beating pressure" (force per fibrage area) to characterize the nature of beating in addition to the consistency of the stock as a means of controlling the cutting action.

In the case of fairly wide flybars and bedplate bars, the actual beating pressure, P, is related to the specific edge pressure P_k (force per length) and the average fiber length l_f, as follows:

$$P \sim \frac{P_k}{\frac{1}{2}l_f} \sim \frac{F_{roll}}{L_{act}\frac{1}{2}l_f} \sim \frac{P_{net}}{L_s\frac{1}{2}l_f} = k\,\frac{B_s}{\frac{1}{2}l_f} \qquad (9)$$

where

F_{roll} = force exerted by the flybar roll against the bedplate

P_{net} = power required to turn the flybar roll in excess of idling power

L_s = cutting length per second

B_s = specific edge load (energy per active cutting length)

k = proportionality constant

Taking into consideration that there is a fairly linear relationship between the edge pressure (force per active cutting length) as defined by Smith and the net power of the beater, one may conclude that the actual beating pressure of Smith is the "forerunner" of the present specific edge load concept.

In other words, assuming that there is a maximum pressure supported by the cell wall, Eq. (9) partially explains why hardwood pulps require considerably less specific edge load than softwood pulps, and why the load carrying capacity of fibers to be refined diminishes as the refining continues (96).

Smith's fibrage theory (131) assumes that the crossing edges of the bars are uniformly covered with fibers. Figure 5 shows values for the fibrage coverage as reported by Smith[1] based on swinging by hand a square cross section rod with a speed of 9 to 10 m/s through the stock. As can be seen from Fig. 5, the average amount of fibrage varies greatly with consistency and with average fiber length, ranging from 0.5 g/m for short fibers at low consistency to 6 g/m for longer fibers at higher consistency. Smith reports (131) that at higher consistencies the fibrage coverage tended to be irregular unless the rod was moved at higher speeds. The amount of fibers deposited increased rapidly with speed.

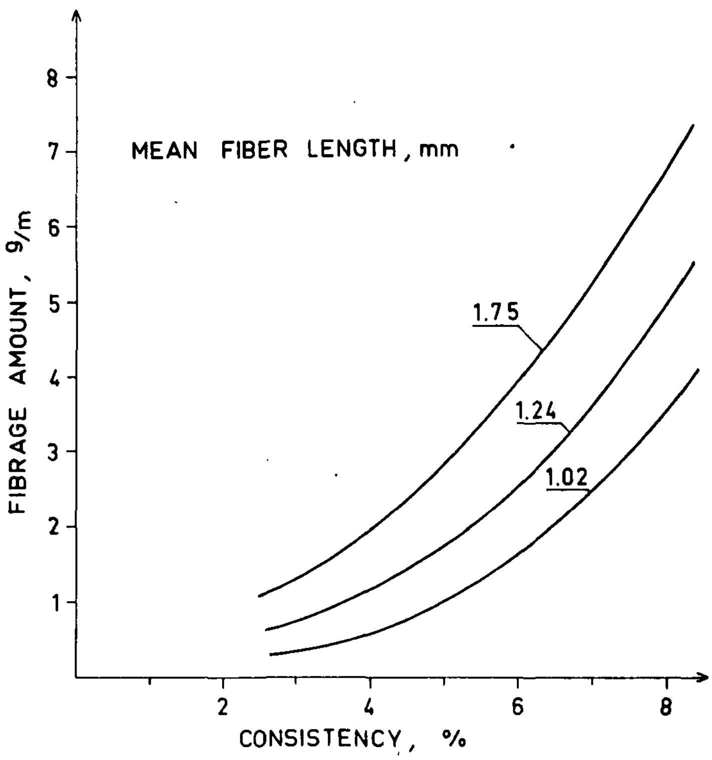


Figure 5. Amount of Fibrage Formed on the Leading Edge of Rod Moving Through Stock (Smith, 1923)

[1]The type of furnish is not reported, but there are indications that it could have been bleached softwood sulfite.

Stephansen (5) has experimented with formation of fibrages under ideal model study conditions. Figure 6 shows his result for bleached sulfite softwood pulp at 3% consistency. The fibrage coverage obtained is of the same order of magnitude as Smith's results. Stephansen reported a value of 3-4 g/m at 10% consistency and with 2 cm approach distance and 5 m/s approach velocity. There is, however, a contradiction between Stephansen's and Smith's results. Smith reported an increase in the fibrage coverage with speed while Stephansen observed just the opposite (Fig. 6). Based on the mass flow through industrial size refiners and on their cutting length per time unit, Stephansen estimated that, on an average, the fiber has a probability to be in a fibrage position about 8 times during its passage through the refiner. This, according to Stephansen, means that a considerable amount of fibers will be treated during the passage. Stephansen also reported that the consistency of deposited fibrages increased with speed, i.e., for 3% stock the consistency of fibrages was about 6% at 1 m/s approach velocity and about 12% at 16 m/s approach velocity. No word was mentioned about the regularity of the deposited fibrages.

Recently Maslakov (132) has analyzed the refining process from a fibrage formation viewpoint. He concluded that the amount of fibrages for an unbeaten pulp was around 4-4.5 g/m for a wide variety of disc refiners and softwood pulps. For a highly refined pulp the corresponding amount was predicted to be 0.5-0.6 g/m, and it corresponded to a monolayer of tightly packed fibers on the bar edges. Maslakov speculated that the sliding of the refined "fibrage" fibers over the bar edges due to their short length and slimy appearance greatly reduced the load carrying capacity of the refiner.

Based on a study of the compressive and shearing forces exerted on the bars during refining, Goncharov (134) proposed a fibrage mechanism to account for the results obtained. The local compressive stresses measured were 13 times greater than the average pressure calculated by dividing the axial thrust with the average surface area of "contact" between the rotor and stator bars. Besides, the high compressive stress could only be registered at the leading edge of the bar. The width of this zone was 2.5 to 3 mm and it was independent of the width of the stator bars or rotor bars. Goncharov also claimed that the existence of fibrages could be seen in highspeed movies.

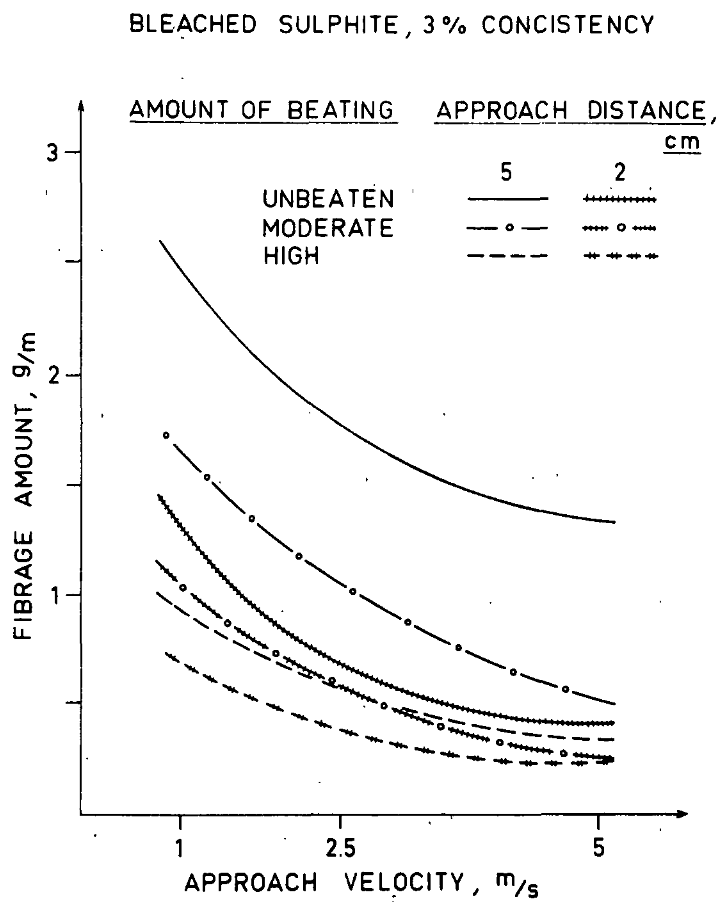


Figure 6. Amount of Fibers Collected on Bar Edge During Model Studies (Stephansen, 1967)

On the other hand, based on high-speed movies of a pilot conical refiner, Page and coworkers (124) reported no homogeneous existence of fibrages at the leading edges of the rotor bars. The same conclusion can be made from the high-speed movie of Halme and Syrjänen (122).

Thus, one has to conclude that, although the fibrage theory of Smith (131) is the only quantitative treatment of the refining mechanics, there is no conclusive experimental evidence available to support the formation of homogeneous fibrage coverage on the loading edges of crossing land areas during LC-refining.

Beating as Lubrication Process

Rance (133) and Steenberg (100) published results in 1951 where the refining had been analyzed as a lubrication process. Rance studied the lubrication behavior of a high-speed refiner and of a Jordan while Steenberg used a Valley hollander in his studies.

According to Rance (133), in the case of a high-speed refiner, the shell setting curves offered indirect evidence of the occurrence of (a) fluid (hydrodynamic) lubrication, (b) boundary lubrication, and (c) lubrication breakdown, which ended up into excessive metal wear or sizing up of the refiner. It was stated that the most economic refining should be done at loads near the breakdown of the "lubricating fiber film."

The hydrafiner was depicted to be operating under such conditions, i.e., at loads near the lubrication breakdown conditions, and the refining action under these conditions involved a high degree of surface fibrillation with some fiber shortening due to shearing. The Jordan instead was visualized to be working under conditions of lubrication breakdown, i.e., with pressure and peripheral speed such that a stable lubricant film could not be maintained. According to Rance, a pulp that exhibited a rapid gap reduction in a Valley beater test was a low quality pulp for industrial refining under boundary lubrication conditions. Similarly it was speculated that the reduction of load carrying capacity during beating was related to the accompanying reduction of the average fiber length.

Rance, however, warned about drawing too many conclusions from the lubrication theory to refining, since in beating one wants to alter the lubricant, i.e., change the character of the fiber, while in lubrication the quality of the oil should remain unaltered.

Steenberg (100) carried out his experiments with a Valley beater varying the consistency, load and peripheral speed. Figure 7a shows the variation of the apparent friction coefficient (μ) with load (F), consistency, (c), and time (t). Figure 7b shows the dependence between the coefficient of friction and the consistency at various loads during initial beating, and Fig. 7c shows the decrease of the apparent viscosity of the pulp during beating based on "force fitting" the various time curves of Fig. 7a into a master curve shown. The pulp used in the experiments was a hot alkali treated dissolving pulp, i.e., a pulp of extremely slow beating. Steenberg stated that the fall of the viscosity would be considerably larger in the case of fast beating pulp.

Based on results in Fig. 7 one may conclude that Valley beating is carried out under hydrodynamic (fluid) lubrication conditions, and that the work absorption capacity, i.e., coefficient of friction, decreases with beating as does the apparent viscosity of the pulp. Steenberg also showed that the gap holding capacity of a pulp during refining is not solely dependent on the average fiber length, but irreversibly related to the slime formation tendency of the pulp.

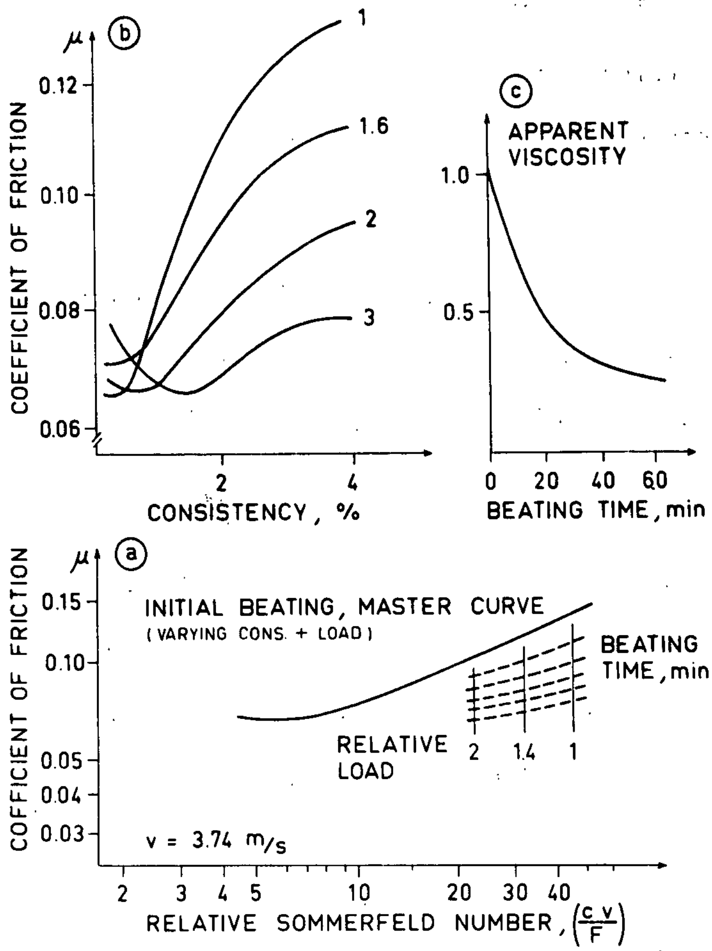


Figure 7. Apparent Viscosity and Coefficient of Friction of Dissolving Pulp During Beating (Steenberg, 1951)

The reported values for coefficient of friction by Steenberg vary between 0.06 and 0.14; higher consistencies and lower loads giving larger values. Goncharov (134) reported a value of 0.11 for the coefficient of friction of refining sulfite pulp in an industrial disc refiner at a consistency of 2.5 to 3%. This value was obtained by dividing the tangential force measured with a strain gage device on the stator bar with a simultaneously measured normal force. The value of the friction coefficient decreased towards the periphery. When the average coefficient of friction is estimated from the net turning power and from the axial thrust given in Goncharov's article, one obtains a value of μ = 0.05-0.08. This difference between the locally measured coefficient and coefficient calculated from the overall force and power balance seems to indicate that the lubrication phenomena during refining are highly local.

Figure 8 shows the results of Goncharov's measurements (134). Figure 8a applies to a case where the distance between the land areas of the rotor and stator bars is large (0.15-0.3 mm) and the possible fibrage coverage very small. In this case the maximum calculated pressure against the land area of the bar edge was below 2 MPa (20 atm.). In Fig. 8b the maximum calculated pressure is around 3.5 MPa (35 atm.) and it corresponds to a case where the specific edge load is 1.5 Ws/m of cutting length. In this case the specific compressive stress is practically constant for a penetration distance of 2.5 to 3 mm between the bars (distance a in Fig. 8b). Goncharov explains this by the squeezing of two fibrages into the advancing gap (Case 1 in 8c). This causes the phase of the maximum compression stresses. It is at this stage, claims Goncharov, that the most intensive refining action takes place through carding and crushing. If the fibers are placed under too high shear stresses at this stage or during the following separation phase (Case 2 in 8c), they will break in tension[1]. During the phase 2, the pressure quickly decreases (distance b in Fig. 8b) to a level which is only about 10 to 15% of the maximum pressure.

One could perhaps advance the explanation given by Goncharov by speculating that if the fibers really enter into the advancing gap as thick fibrages, the compressive stresses that these shearing fibers will support are large enough to cause tremendous movement of water inside the cell wall and aid in creating internal fibrillation and external fibrillation. The latter effect of refining is, of course, greatly accelerated by the mutual rubbing of the fibers.

[1]Steenberg (4) has speculated that the shortening of the fibers during refining is through tension failure and not through cutting, since the ends of broken fibers become highly fibrillated

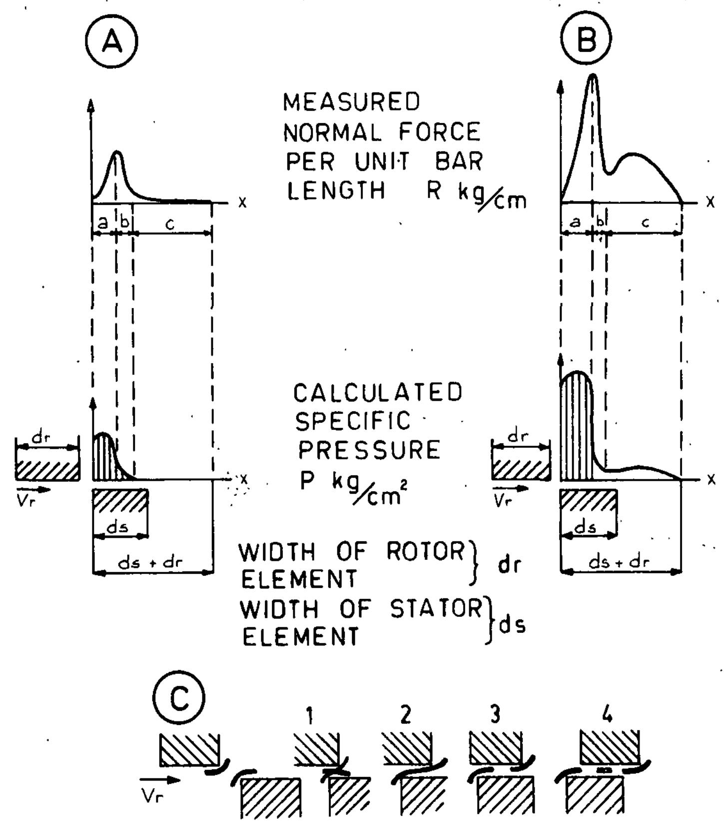


Figure 8. Fibrage Induced Bar Forces (Goncharov, 1971)

Type and Degree of Treatment Concept

In this theory, refining is actually considered as a black box operation which can be controlled by an intensity term and by an extent term. The theory usually bears a name: "Specific Edge Load Theory of Refining," and it is usually credited to Brecht and coworkers (135,138) who advanced the specific edge load idea of Wultsch and Flucher (98).

However, the idea of a certain type of specific edge load had already been used by Smith in 1951 (139) in trying to explain differences in the quality of hollander and refiner beaten stock. Moreover, Cottrall (103) states the significance of increased edge loading as: "At higher loads, the fiber film between the bars gets thinner. This has two effects - (1) less fibers get between the bars in each pass, so that less fibers are treated at each pass and the proportion of untreated fibers is greater - (2) the fibers that are treated are more intensively treated ...."

In connection with the specific edge load theory, one should remember that Lewis and Danforth (140) proposed already in 1962 that the stock preparation process should be expressed as a function of two independent components, namely (a) number of impacts between the tackle edges to which the fibers are subjected and (b) the severity of such impacts (Fig. 9). This idea was later developed to a quantitative characterization of refining by Danforth (141). Also one should remember the pioneering work of Van Stiphout (142) in characterizing the nature and extent of the refining conditions. Van Stiphout apparently was also the first to use the concept of plotting the dependence of the refining result as constant value curves (isocurves) in the amount of refining and quality of refining coordinate system. Van Stiphout concluded from his result that refiners of greatly different size, tackle, and rpm can be made to treat the pulp in quite the same manner, provided that the two components for the characterization of the refining conditions are about the same. He also proposed that the refiner for a paper machine, with a variety of paper grades, should be equipped with a variable speed transmission. The same idea has later been advocated by Arjas (143).

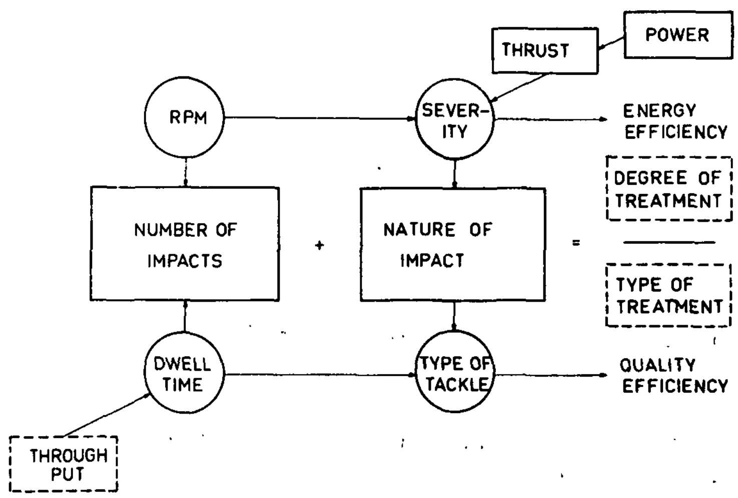


Figure 9. Basis for Analysis of Stock Preparation (Lewis and Danforth, 1962)

Leider and Nissan (117) have also derived equations to characterize the number of impacts and energy released per impact. Some criticism has been directed towards the assumptions under which the equations were derived (151). Lately Kline (152) has proposed that the intensity of refining should be characterized by net horsepower applied divided by effective (average) refining area, and the amount of refining should be characterized by a term related to the quotient of the effective (average) refining area divided by the mass flow of pulp. The product of the intensity and amount terms will give the specific net energy consumption of beating.

The specific edge load theory is based on a tacit assumption that the major part of the refining action is due to the deformation induced by the impact of opposing rotor and stator bars as they cross over each other. This impact phenomenon is directly related to the "cutting speed" L_s (edge length per second, inch cuts per second). The power consumption of the refiner, P_{total}, is divided into two components, P_{idle}[1] describing the power with the rotor in the backed-off position and water flowing through the refiner, and P_{net}, which is the difference between the total power consumption and the idling power. The intensity of refining is defined by the term specific edge load, B_s, which is

$$B_s = \frac{P_{total} - P_{idle}}{L_s} = \frac{P_{net}}{Nl_s} \qquad (10)$$

where

$L_s = Nl_s$, i.e., rps times the total cutting length of the refiner in question.

[1]Steenberg (167) has criticized this principle, since the fibers suspended in the water change the viscous drag of pure water considerably.

The amount of refining is defined as "specific net energy consumption," W_e and it is

$$W_e = \frac{P_{total} - P_{idle}}{\dot{m}} = \frac{P_{net}}{\dot{m}} \tag{11}$$

where

$\dot{m}$ = the mass flow of pulp (dry) through the refiner.

Based on an extensive series of experiments, Brecht and Siewert (136-137) concluded that the refining result of a given pulp is unambiguously defined when the B_s and W_e of the refining treatment have been the same. In other words, the width of the bars, the number of the bars, their average contact area, rpm, consistency, and volume flow have no other effect on the refining than that included in the definition of the terms B_s and W_e.

Later studies have, however, shown that the specific edge load theory is not a comprehensive system for characterizing the refining conditions and predicting the refining results. For instance, it does not take into account the effect of the bar material and the sharpness of the leading bar edge on the intensity of refining (see Current Facts about the Refining Process) and it does not take into account the effect of consistency[1] on the intensity factor (144) or the effect of impact angle, direction of rotation, rpm, and depth of the grooves (18,144-147) on the intensity and amount factors of refining. The specific edge load theory has also been criticized because it puts too much emphasis on the impact phenomenon when the opposing bars pass over each other. Note there are plenty of efficient refiners in industrial use where the impact phenomenon - in the sense it is included in the specific edge load theory - is totally missing. For instance, in the Vargo refiner

[1]Both the analysis of Van Stiphout (142) and of Danforth (141) included consistency in the intensity and amount terms.

(148) and in the refiners equipped with basalt tackle (149,150) one may obtain excellent refining results with considerably less energy consumption than in the case of conventional bar filled refiners.

One can conclude that, although the specific edge load theory of refining has greatly clarified the effect of various design parameters of the bar filled refiners on the refining conditions and on the obtained refining action, and although it has properly emphasized the important role of the specific edge load in the intensity factor of refining, it has, perhaps unduly, stressed the scissor-type cutting action in the analysis of refining mechanisms.

Transport Phenomenon in Refining

Mention has already been made of the role of reversing flow in the grooves of the stator (20,119,122) and between the grooves of the rotor and stator tackles (121). These flow patterns define the gross pulp transport through the refiner. The transport phenomenon can be analyzed (a) from the flow behavior viewpoint and (b) from the viewpoint of residence time distribution of pulp fibers inside the refiner.

Flow Behavior

Banks (119) described results of high-speed cinematography of pulp flow through an experimental transparent disc refiner. The quality of the film did not allow a detailed analysis of the flow behavior of fibers inside the refiner. Fibers and flocs were seen to get stapled against the leading edge of the stator bars. The land area of the stator bar covered by these fibers and flocs was about 50 to 70% of the width of the stationary bars[1]. The flocs remained on the stator bar for at

[1]No information was given about the consistency of the pulp or the width of the stator bars.

least one rotor revolution. More pronounced floc collection was observed towards the disc periphery.

Fox and coworkers (153,154) have reported results of a high-speed cinematographic study of the flow behavior of fibers inside a transparent disc refiner. The studies were carried out with bleached southern kraft pulp using consistencies of 0.1 to 0.3%. Their results are summarized in Fig. 10.

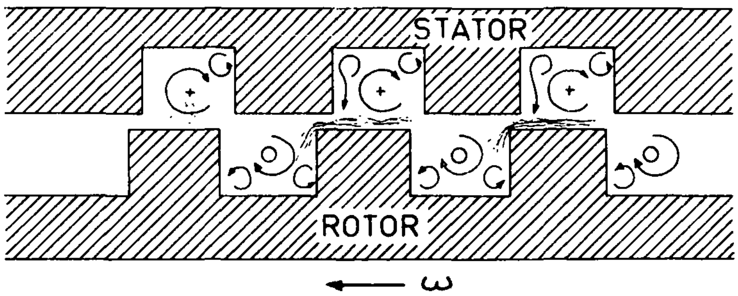


Figure 10. Internal Flow Field and Transport of Fibers Inside a Disc Refiner (Fox, Brodkey, Nissan, 1979)

Fox and coworkers named the various flows as follows:

(a) primary radial flow that is outward in the grooves of the rotor tackle and inward in the grooves of the stator tackle,

(b) secondary vortex in the above mentioned primary flows due to the "spinning" introduced through the friction of the land area of the rotor bar when sliding over the groove of the stator and by the land area of the stator bar when sliding over the rotor groove, and

(c) tertiary flow resulting from the secondary vortex flows in the corners of the grooves. In the case of the stator groove, the vortex flow above the corner of the leading edge of the stator bar is modified into a tertiary wiping flow over the leading edge. The driving force for this flow is the higher pressure that exists in the stator groove.

Fox and coworkers (153,154) proposed that this tertiary flow empties fibers from the stator grooves into the refining gap and holds them against the leading edge of the rotor bars. Stapling of the fibers was not observed against the leading edge of the stator bars in the high speed movies except at the periphery of the stator tackle. The authors hypothesized that it is the stapled fibers that receive the refining action and after breaking loose they either become part of the inward stator flow and perhaps get stapled again or they become part of the outward rotor flow and may leave the refiner or be reverted back to the stator through the outside annulus of the refiner. In a later paper Fox (154) proposed that high levels of fluid and mechanical shear act to cut and refine the stapled stock and that three modes of delivery are involved in delivering the stapled fibers to the periphery. These proposed modes are: (a) release delivery, (b) slip delivery, and (c) sweep delivery. The last mode is pictured to take place only in the so called exit-flow region, i.e., in those rotor and stator grooves which connect the inlet flow region to the exit region. Fox also proposed that there is an optimum angular velocity at which the stapling is maximized. As evidence for this proposal, Fox presented results which indicate that there is a maximum in the thickening effect of the refiner as a function of rpm. In other words, the average consistency of the stock inside the refiner is higher than the consistency of the inlet flow because of the stapling phenomenon.

Since the main work of Fox and coworkers (153,154) was based on extremely low consistencies and since the bar clearance during the test runs was fairly high ($\geqq$ 0.15 mm), the results do not necessarily apply to industrial refining, where the bar clearance is considerably smaller and the fibers are not able to move independently because of the network restrictions originating from the higher consistency of the stock. Besides, there is a discrepancy between the results of Banks (119), who observed stapling against stator bar edges, and those of Fox et al., where stapling was observed mainly against the rotor bars.

Residence Time Distribution

Ryti, Arjas and coworkers (101,155-161) have studied in considerable detail the role of residence time distribution in refining. The starting point of the study was that the refining action is related to the residence time inside the refiner and to the probability of treatment during this time. In other words, their starting point follows the earlier idea of Steenberg (4), who stated that the refining action is a result of a selection process and of a treatment process. In practical studies, Ryti and Arjas concentrated only on the analysis of the residence time, discarding the contribution of the probability function. The tacit assumption in their studies was that the beating result is better the more uniform the refining treatment has been[1].

In the preliminary experiments it was observed that systematic differences existed between the drainage properties of the stock and the physical properties of the handsheets when continuous refining in the Valley beater was compared, at equal effective refining time, with the results obtained from normal, "batch type" Valley refining (101,155). The differences were not statistically significant. For instance, when tear was plotted as a function of tensile or scattering power as a function of tensile no significant difference was observed between the two sets of refining in the Valley beater, i.e., the type of refining action produced by the continuous and by the batch operation of the Valley beater did not differ significantly. However, the authors concluded that the results of the preliminary

[1]The practical application of this assumption may be questioned, since in most cases of industrial paper production it has been found that significant economical and property advantages can be obtained by using a mixture of various types of pulp fibers as a raw material for paper.

experiments support the hypothesis that the shape of the residence time distribution curve affects the papermaking properties of the pulp.

In a later study (158) an attempt was made to study the effect of flow rate and angular velocity on the shape of the residence time distribution curve. The residence time curve was measured inside a mill scale conical refiner with conventional pulp fibers tagged with a radioactive chemical. No clear-cut effect of the two studied variables on the RTD-curve could be observed because of very large scatter of the recorded signals. Based on the use of a special levelling technique (157), the authors concluded that the qualitative information was in accordance with the flow behavior one would predict from the role of return flows inside the refiner. Similar information has been observed also in residence time distribution studies of the disc refiner (125), i.e., the flow rate has an effect on the mean residence time, but the effect of the angular speed is not very large. In the last set of experiments (160) the effect of residence time distribution in a mill scale conical refiner on the properties of an unbleached pine kraft pulp was studied. The average residence time was kept constant and comparisons were made between continuous refining (a) in four refiners connected in series, (b) in one refiner, and (c) in one refiner connected with a mixed recirculation tank. The authors concluded that four-fold passage through a refiner produced a more homogeneous refining action than the one-pass refining in accordance with the theory (156). However, again the observed differences in the handsheet properties were not statistically significant. The same result concerning the sharp *vs.* wide RTD of refining has already been presented by Maynard (102) after studying refining with a high-speed conical refiner equipped with a recirculation valve. Even in the case of refining with recirculation through a mixed chest *vs.* four-fold or direct passage through the refiner, Arjas and coworkers did not get any significant differences in the beating response (160). Similar results have been reported by Leider (162).

The theoretical treatment of series connected refiners by Arjas (156) gives a different conclusion than the analysis by Korda (163), who came to the conclusion that refiners should be connected in series but equipped with a recirculation flow after each refiner in order to secure the most homogeneous treatment of fibers.

It has been shown that with conical refiners, where the cutting angle between rotor and stator bars differs by about 0°, the residence time distribution curve is sharper (145). It has also been shown (146) that when the mean residence time in the disc refiner decreases while the specific edge load stays constant, the refining becomes more intense, especially in the case where softwood pulps are refined. A statement has also been made that the dwell time inside a disc refiner is only about 1/10 of that in a conical refiner (118).

It thus seems that the average residence time inside the refiner - and especially inside the refining zone[1] - has an effect on the type of refining action experienced by the fibers. However, it seems debatable that refiners connected in series would give a significant advantage in actual refining over parallelly connected refiners. This is especially so if one keeps in mind the flexibility requirement of industrial refining systems. Besides, none of these studies can be used as a guide for how to split the energy of refining between the various refiner units in a series connection case.

It seems to the author that if the role of the residence time distribution curve in refining is to be clarified, one needs to follow the basic analysis of chemical engineering reaction kinetics as, for instance, outlined by Levenspiel for cases with various types of feed-back flow of macrofluids (164). In other words, it is not enough to look only to the residence time distribution. Instead one has to

[1]It should be kept in mind that the actual bar area volume of the refiner is only about 20-25% of the inside volume of the disc refiner and considerably less in conical refiners.

take into consideration also the reaction kinetics, i.e., the treatment function (probability and type of action received).

Descriptive Models

Reference has already been made to the analysis of refining by Steenberg (5). Steenberg stated that several subprocesses, each one having a major influence on the refining result during certain phases of refining, are functioning in refining and therefore a single parameter cannot be used to describe either the process or the state of the product (i.e., beaten pulp). Steenberg advocated that at least two of the subprocesses, namely the selection process and the treatment process, should deserve more attention. He also stated that too much emphasis has been placed in the past on direct tackle-fiber interaction as a mechanism of transferring refining action into fibers and the interaction effect between the fibers has obviously been overlooked. This interaction was visualized to be high enough - because of the network structure of the stock - to cause external fibrillation and crill formation plus increase the flexibility of the fibers and perhaps causing shortening of the fibers through shear-induced tensioning.

Giertz (32) postulated that the intensity of the refining forces acting on fibers can be described by a distribution function (Fig. 11). The problem in industrial refining was depicted to be, that when the intensity of refining was increased in present refiners, the relative role of "unproductive" refining action still stayed at a high value, explaining the low energy efficiency of refining. The same conclusion has been presented by Leider and Nissan (117).

Clark (16) has summarized the mechanics of refining action in a descriptive way. In Clark's treatment one, two or more fibers are depicted between the approaching bars (Fig. 12). A shear force field can accomplish shortening of fibers through shearing tensioning (directly or through the network) and crushing.

Internal and external fibrillation plus production of debris is pictured to take place through abrasion by the bar surfaces and through rolling and twisting action of individual fibers or of several fibers in the bar gap. Dislocations were pictured to form when a floc was being squeezed into the gap between opposing bars.

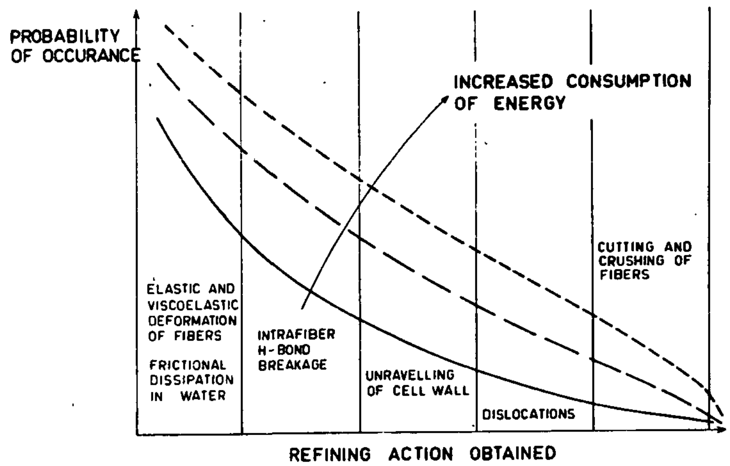


Figure 11. Distribution Curve for Refining Forces (Giertz, 1964)

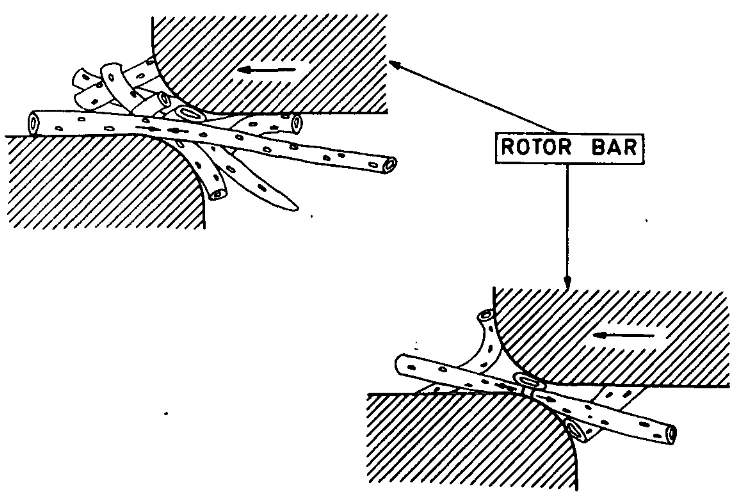


Figure 12. Description Representation of Some Bar Actions in Refining (Clark, 1978)

Steenberg (19,165) has analyzed the refining process as an irreversible kappa process, which involves a critical path for the formation of a stress concentration chain, in which a structural breakdown will occur. For another structural breakdown to occur the particles, i.e., fibers, need to be rearranged.

According to Steenberg there is a threshold consistency below which the formation of a stress concentration chain is impossible because the fiber slurry will "ooze" (i.e., escape the force which is trying to accomplish the stress concentration chain). Above the threshold consistency the network will consolidate under the action of the refining force and a critical path of stress concentration will occur and cause a major primary effect of refining. The threshold consistency will depend, besides on the quality of pulp, on the overall consistency of the stock, on the rate of movement of the force transferring surfaces and on their relative distances, and on the state of beating of the stock. Increased beating will move the threshold consistency towards higher values. The grooves of the refiner play an important role, according to Steenberg. They allow efficient mixing of the pulp fibers to take place after the kappa process and thus generate a new configuration for the next kappa process. A similar idea has also been proposed by Halme and Syrjänen (122). It should also be noted that the oozing/consolidation phenomena takes place in Kollergang refining (166) and that it is impossible to refine in the Kollergang if the overall consistency falls below a certain value.

"Treatment of Flocs" Hypothesis

In the 1951 symposium on beating, Steenberg (100) showed that the gap holding capacity of the Valley-beater could - almost instantaneously - be reduced by adding to the stock a certain amount of slime producing substances (Fig. 13). Based on this observation Steenberg questioned the then accepted idea that the gap is related to the average fiber length of the stock to be refined (133). Later Arjas (101) has reported that when unrefined fibers were quickly replaced into a Valley-beater when the beating was in progress, the instantaneous increase in the gap was related to the amount of stock being replaced, but the decay of the instantaneous gap increase was faster the later in the beating the replacement was done.

During the discussions of the 1951 symposium an idea was proposed that the observed gap effect could be due to dispersion of flocs (168). The highly unstable and erratic gap in the early stages of Valley-hollander beating (169) could afterwards also be considered as a possible indication of flocs being present in the gap.

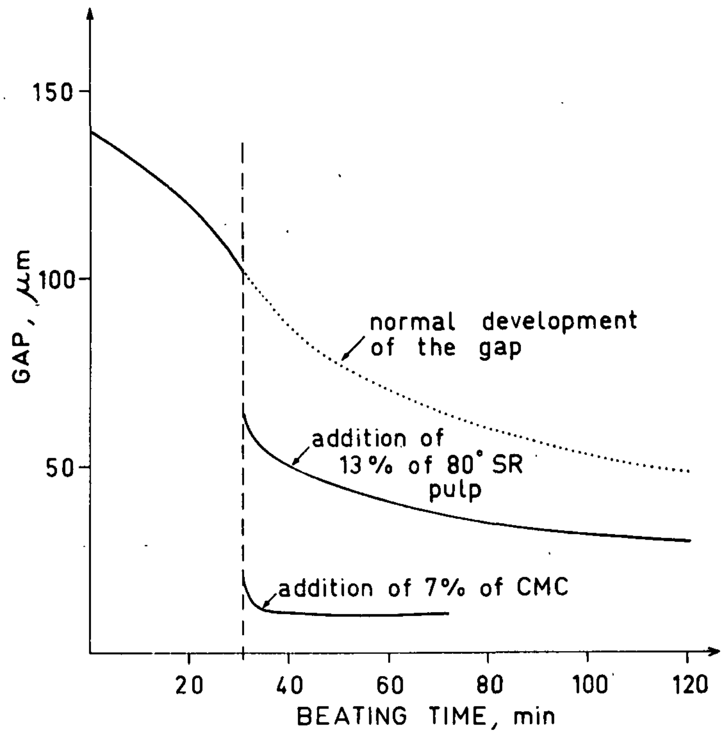


Figure 13. Development of the Refining Gap During Valley-Hollander Beating of Sulfite Pulp (Steenberg, 1951)

The idea that the refining of pulp fibers should actually be considered as refining of mainly flocs did not gain any popularity, although indirect evidence seemed to speak for it. In 1957 Steenberg (170) cited an example that it was impossible to pass fibers through an experimental disc refiner unless it was equipped with semisphere holes linked to each other in succession in rotor and stator discs. He later also reported (171) that it was extremely difficult to measure the viscous shear properties of pulp suspensions in a smooth surfaced plate viscometer because of the presence of fiber bundles and flocs. When narrow radial grooves were machined on the surfaces, an even flow through the measuring zone was obtained.

Page and coworkers (124) apparently were first to actually state that refining involved breakage of flocs and treatment of the remnants of these flocs between the rotor and stator surfaces. They derived their conclusions from high-speed photography of a conical refiner. According to them, the refiner is inefficient since only a small proportion of fibers are where they should be.

In 1967 Banks (119) - based on high-speed cinematography and on contributions by Espenmiller - summarized the mechanics of refining as follows:

1. Flocs consolidate when they are trapped between approaching tackle elements.
2. Mechanical pressure induced by the tackle elements becomes high enough and causes plastic deformation in the fibers composing the floc. Consolidation continues.
3. The floc compressed between the bars is sheared; flocs (and fibers) are ruptured.
4. Release of mechanical pressure allows absorption of water to take place into the ruptured fibrils and fibers.
5. Turbulent agitation may disperse the floc or its remnants into the general mass flow.

According to Banks, the floc treatment theory differs from the fibrage theory in the local action aspect since the fibrage theory assumes a complete uniform coverage of the bar edges. As a matter of fact, the hypothesis of Banks (119) is similar in many respects to that expressed by Page and coworkers (124).

The new and important aspect of this hypothesis for the theory of refining is that fibers are not treated as independent particles, at least in the beginning of refining, but that they take part in refining as entities of macrostructure, namely as flocs. The probability of a floc getting sheared in between the crossing land areas of the rotor and stator bars is several orders of magnitude smaller than that of an individual fiber. On the other hand, if and when the floc gets entrapped between the bars, the result of refining action may be considered catastrophic for the majority of those fibers which form the floc.

The idea of refining flocs instead of individual fibers is by no means unnatural. It is well established that fibers form strong networks at 2-4% consistency and that, when such networks break up, flocs are formed.

As an additional piece of indirect evidence for treatment of flocs in refining, the noise phenomena during refining should be mentioned. It has been established that the noise level of refining with a hydrafiner goes down very rapidly at the beginning of refining (98). The starting level and speed of decrease was higher for "strong" pulps than for low yield "soft" pulps. The reduction in noise level was most pronounced in the higher harmonics of the "bar contact" frequencies.

NEW EVIDENCE FOR THE HYPOTHESIS OF "TREATMENT OF FLOCS"

Recent high-speed cinematography studies (172) have shown beyond any doubt that the hypothesis of "treatment of flocs" describes the fundamental phenomena in transferring the refining action into the fibers (Fig. 14,15). Movies were taken with a speed of 1000 frames per second. The peripheral speed of the 12 inch disc was gm/s. The film speed was not high enough to stop the rotor bar; it moved about 3 mm during the exposure. A bleached southern pine kraft at 1.1% consistency was used. The gap was about 0.15 mm. The transparent experimental refiner has been described by Fox (153,154). Just before filming, a small amount of black dyed pulp fibers was injected into the eye of the refiner.

The enlarged film frames (Fig. 14,15) show a fairly dark band across the frame. That is the stator groove. The width of this groove is 6 mm. Across this groove are seen the rotor bar edges. The angle between the rotor and stator bar edges is about 20°. In some individual frames the contour of rotor bar edges has been outlined. If there are no fibers between the land areas, then the light from the opposing side of the refiner will pass with ease to the lens of the camera, which is aimed into the light passing through the refiner from the stator side. If there are plenty of fibers between the land areas, the dark flocs will show up as black areas in the crossing of the land areas. If there are plenty of dyed fibers in the rotor groove while it is over the land area of the stator bar, the rotor groove will show up as a light gray band against a white surrounding.

Figures 14 A and B plus 15 A and B show that only occasionally can one find fibrous material between the land areas. Based on an analysis of the film, one could perhaps state that only about once in every ten successive land area crossings is there plenty of fibrous material in between. The shape and optical density of

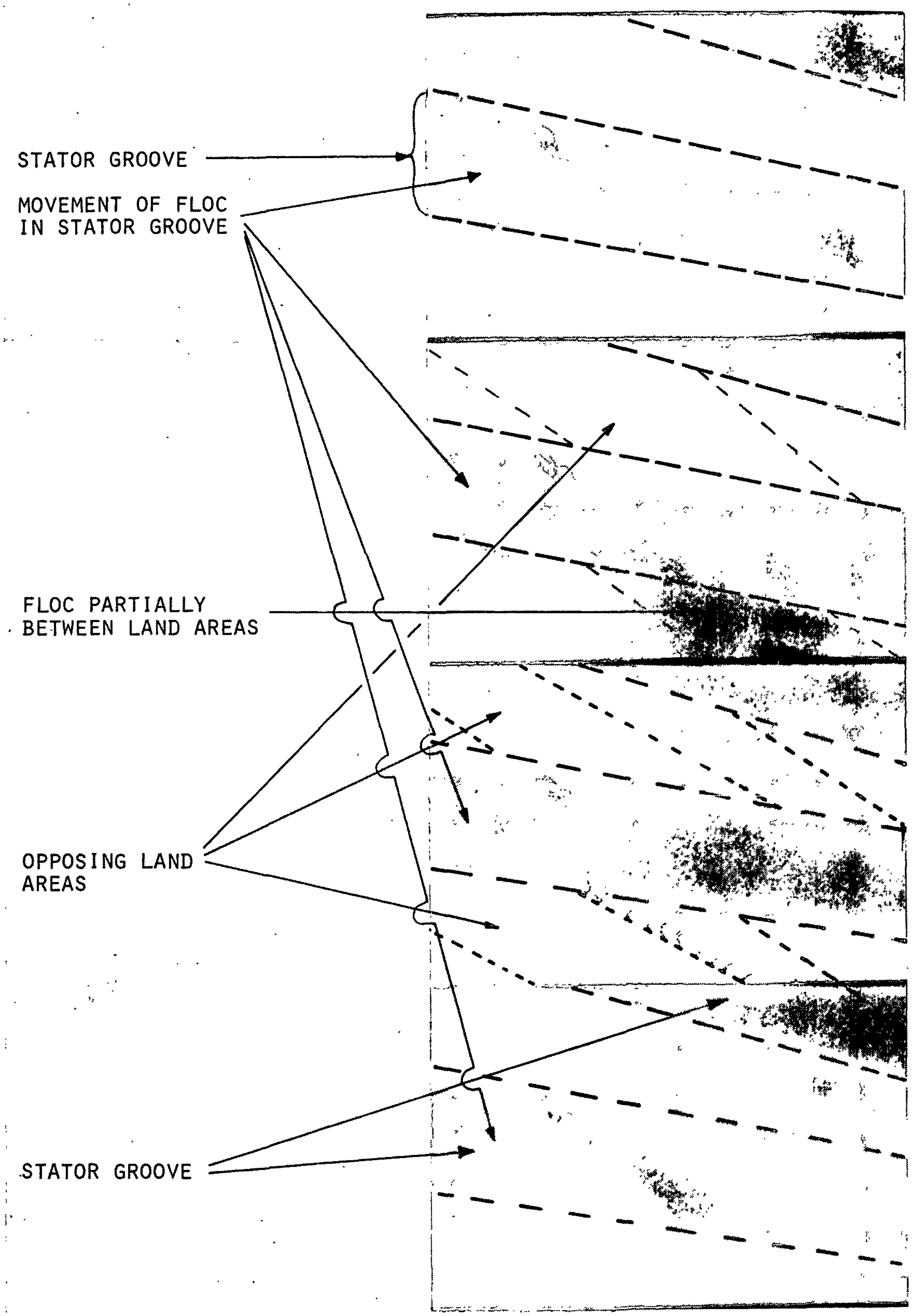


Figure 14. Enlarged 16 mm Film Frames Photographed Through Transparent Experimental Disc Refiner (Successive Frames Exposed at 1/1000 s)

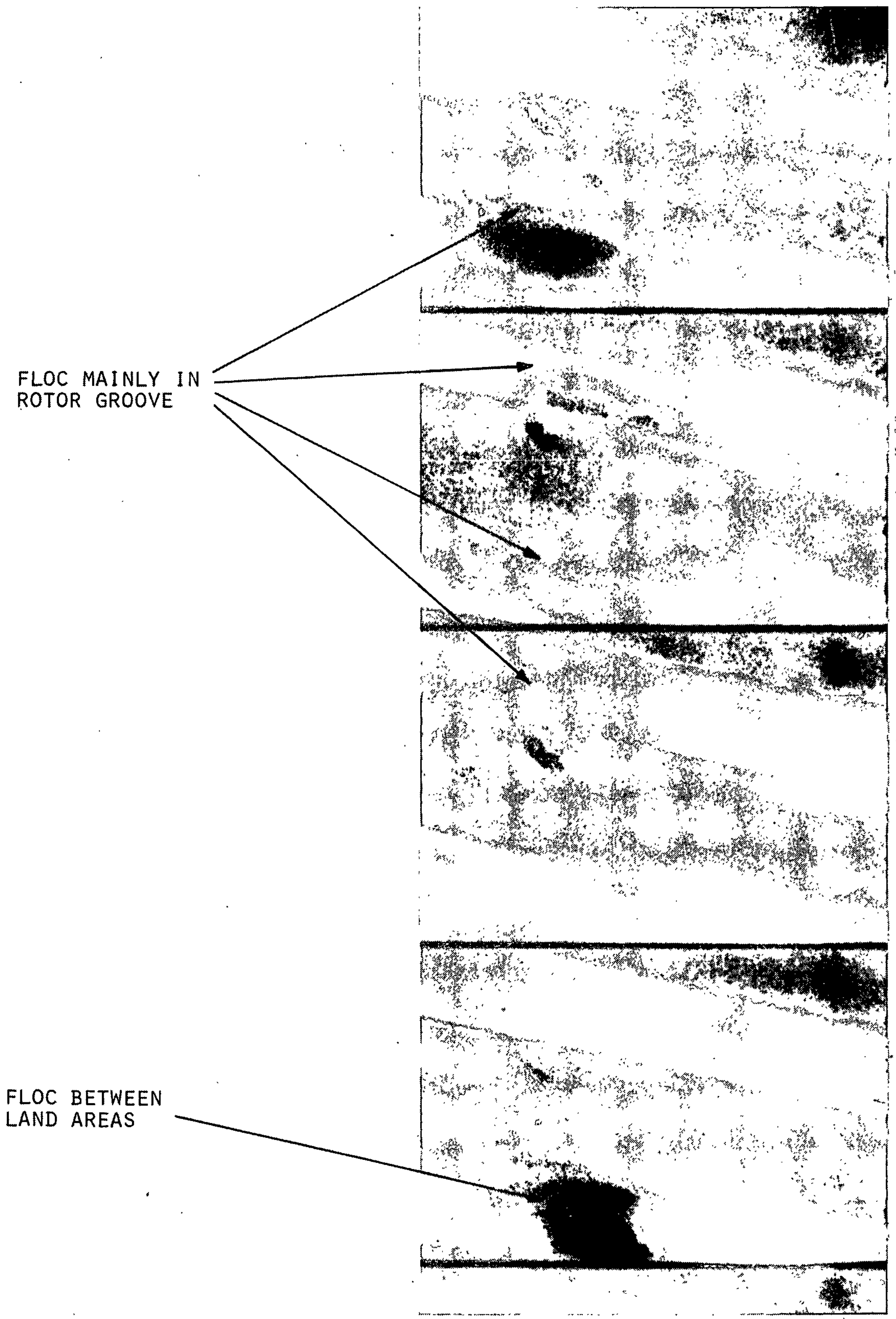


Figure 14. Enlarged 16 mm Film Frames Photographed Through Transparent Experimental Disc Refiner (Successive Frames Exposed at 1/1000 s)

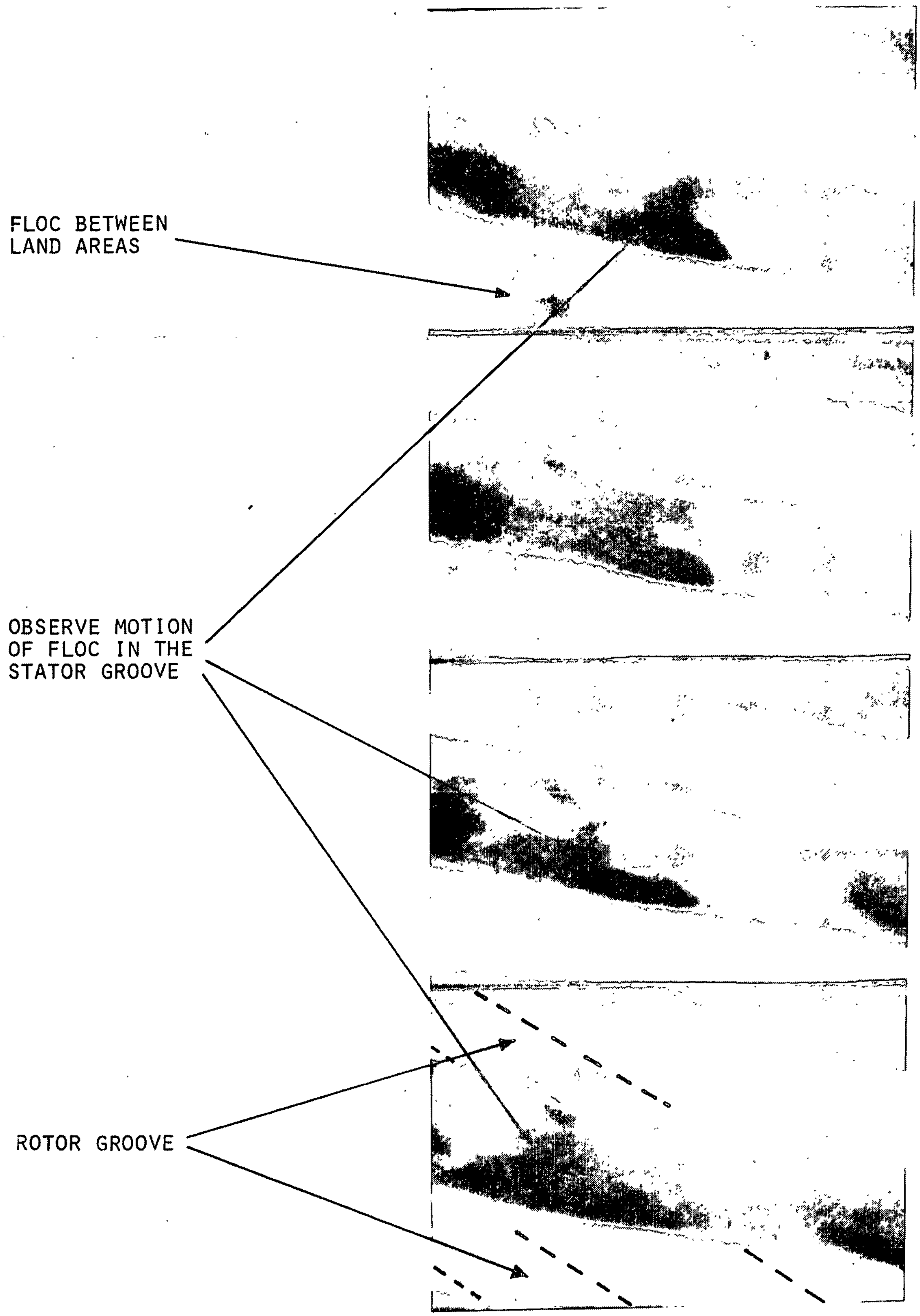


Figure 15. Enlarged 16 mm Film Frames Photographed Through Transparent Experimental Disc Refiner (Successive Frames Exposed at 1/1000 s)

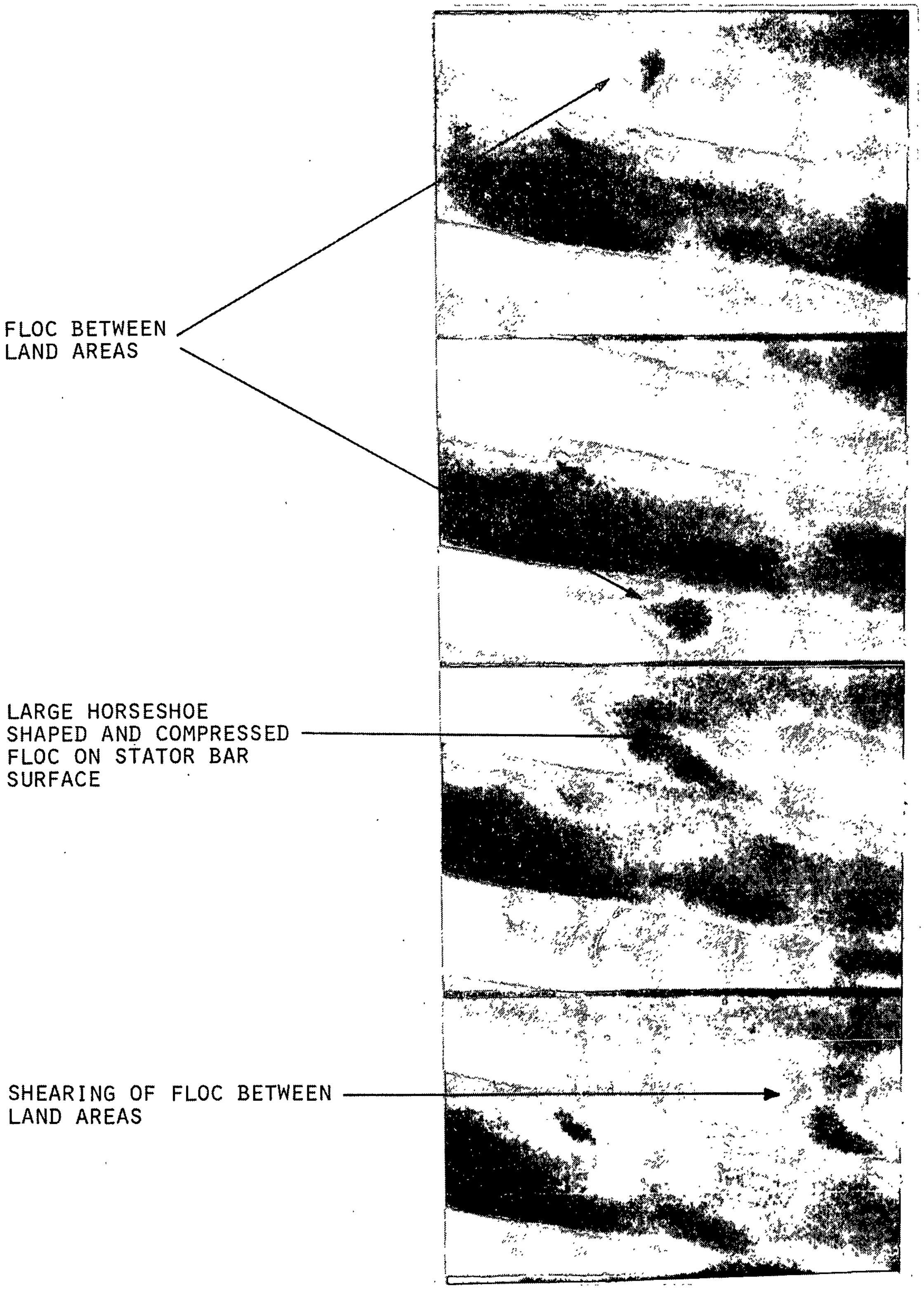


Figure 15. Enlarged 16 mm Film Frames Photographed Through Transparent Experimental Disc Refiner (Successive Frames Exposed at 1/1000 s)

the material suggests that fibers exist as a floc in between the bars. The floc covers only a very small fraction, perhaps around 10%, of the total area of the bar crossing. Thus one arrives at the conclusion that the pressure supported by the flocs could be up to 100 times higher than the average vectorial pressure between the plates. In other words, the flocs may be under a compressive stress of well over 10 MPa (100 atm.). This high stress can easily squeeze water out of the cell wall of the fibers even during the short period of a bar crossing (~0.2-0.5 ms). The layered structure of the cell wall will be exposed to enormous forces.

Based on the above analysis, it can be postulated that the compression induced movement of water inside the cell wall is a primary factor, contributing to the so called internal fibrillation. Similarly, it can be postulated that the estimated compressive forces on a cell wall level are high enough to cause cutting of fibers.

The size of flocs at the 1.1% consistency used may be estimated from the flocs visible in the stator grooves. The larger flocs seem to be around 4-6 mm long and 3-4 mm wide. It is not easy to get such a large "particle" to go into the narrow gap.

The flocs do not seem to stay on the stator land area for more than one passage of the rotor bar edge. It is impossible to conclude if the flocs adhere preferably to the leading rotor bar edge as postulated by Fox and coworkers (153,154)(Fig. 10).

This new direct evidence is in line with the hypothesis originally presented by Banks (119).

CONCLUSIONS

As a result of a critical review of the refining literature, one has to conclude that there seems to be a greater unity between the authors about the results of refining action on fibers, i.e., about the primary beating effects, than about the mechanisms which are actually contributing to the formation of the primary beating effects. In other words, the actual mechanics of refining, i.e., the understanding of how mechanical energy is transferred into the fibers and how this transfer causes the various structural changes in the fiber cell wall, is still very speculative. The main reason for speculation seems to be the difficulty of obtaining direct experimental results concerning the mechanics of refining.

Since energy is required for refining, the need for an adequate theory of refining is obvious: with a theory one might be able to increase the efficiency of refining considerably, and obtain combinations of refined fiber properties which are unattainable with today's refining techniques.

One reason for the lack of a theory of refining may be the underestimation of the network and flocculating character of the pulp to be refined. In most of the publications dealing with mechanisms of refining it seems to be assumed that fibers are treated individually and independently in the refining zone. If one accepts the idea that the fibers are flocculated, even possibly turbulent flow conditions existing inside the refiner, then it is easy to extend the fibrage theory of refining into the proposed hypothesis "Treatment of Flocs."

The flocs in refining may be visualized to have a dual role. First, the flocs, because of their large size in respect to the gap dimension, decrease the probability of treatment of fibers in the refining zone, i.e., the flocs decrease the efficiency of refining. Secondly, because a floc is an assembly of a very large number of fibers, it protects many of the fibers from a catastrophic refining treatment, a result which is obtained if the refining is done at stock consistencies below 1%.

The reasoning leads to the following chain of thoughts. In order to increase the efficiency of conventional LC-refining, one should treat fibers instead of flocs inside the refiner. The refining zone should be designed so that all the fibers entering into it have a high probability of treatment. In order to be able to control the refining action specifically, one probably needs several types of refining zones; each of them being tailored to obtaining one or two specific primary beating effects. In order to increase the energy efficiency of today's LC-refining, the treatment zone should be decreased in volume considerably, so that the refining work to be done is concentrated to the small volume of the cell wall, thus minimizing the loss of energy to unnecessary turbulence and to unnecessary deformation of the fibers and flocs. It may also be necessary to develop new materials for the attrition surfaces, matching their properties to the elastic properties of the cell wall structure, which is to be modified by refining.

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Kari Ebeling

Kari Ebeling
Professor of Paper Technology
Helsinki University of Technology
Forest Products Department
Otaniemi, Finland